

Threshold dependence on the spectral alignment between the quantum-well gain peak and the cavity resonance in InGaAsP photonic crystal lasers

J. R. Cao,^{a)} Wan Kuang, Sang-Jun Choi, Po-Tsung Lee, John D. O'Brien, and P. Daniel Dapkus

Department of Electrical Engineering and Electrophysics, University of Southern California, 3737 Watt Way, PHE 424, Los Angeles, California 90089

(Received 30 May 2003; accepted 19 September 2003)

Lithographically defined multiwavelength photonic crystal laser arrays are reported. The dependence of the threshold pump power on the spectral alignment between the quantum-well gain peak and the cavity resonance wavelength is investigated. This is done at, and slightly above, room temperature. © 2003 American Institute of Physics. [DOI: 10.1063/1.1627466]

Photonic crystal (PC) devices have been intensely investigated in recent years owing to their potential to form dense highly integrated optical circuits. PC lasers are important components of such integrated circuits because it is possible to lithographically define the lasing wavelength.¹ In this study, we demonstrate PC laser arrays and utilize the ability to lithographically tune the PC laser cavity resonant frequency to investigate the dependence of the threshold pump power on the spectral alignment between the gain peak and the cavity resonance. We investigate this at, and slightly above, room temperature. This threshold dependence is a crucial characteristic for potential wavelength division multiplexed (WDM) applications.

In this letter, an array of 31 suspended membrane PC microcavity lasers is fabricated in which the lattice constant varies in 2 nm increments between neighboring elements of the array. Removing 19 holes from a triangular lattice of air holes, which perforates a 224-nm-thick InGaAsP membrane on an InP substrate, forms each of these microcavity lasers. The membrane contains four 1.2% compressively strained InGaAsP quantum wells ($\lambda = 1.55 \mu\text{m}$). The quantum wells are separated by 20-nm-thick InGaAsP layers ($\lambda_{\text{gap}} = 1.2 \mu\text{m}$). The triangular lattice PC is defined by electron beam lithography in 2% polymethylmethacrylate. The pattern is then transferred through a hard mask and the semiconductor in a series of dry etching steps. The suspended membrane is formed by a HCl-based wet chemical etch at 0 °C, which selectively undercuts the InP substrate. The ratio of the air hole radius to the lattice constant (r/a) is kept constant across the array at the value of approximately 0.26. More details about the fabrication of this laser structure can be found in Ref. 2. A section of the array is shown in Fig. 1.

The PC lasers in this study were optically pumped with an 850-nm edge-emitting diode laser at normal incidence. The pumping condition used was a 4-ns pulse width with a 0.5% duty cycle at and above room temperature. Of the 31 laser elements in the array, 17 elements lase in the same mode, which is tuned across the gain spectrum as the lattice constant varies.³ These 17 elements are part of 23 adjacent

elements in the array. Six cavities in this series of 23 elements operate in different modes, which are more than 50 nm away from the mode of interest. Here we focus on the 17 lasers operating in the same mode. Each element shows single mode lasing with at least a 20-dB side mode suppression ratio. Figure 2 shows the lasing wavelengths of the elements in the array as a function of lattice constant. Maxwell's equations yield scaled eigenfrequencies when the spatial extent of the dielectric is scaled. Here, we have scaled the lattice constant with a fixed value of r/a . However, since all of these lasers are fabricated in the same epitaxial layers, the membrane thickness (d) is not scaled correspondingly. Nevertheless, the experimental wavelength tuning rate with lattice constant is nearly constant. The average lasing wavelength spacing between elements in the array is 4.2 nm. These wavelength tuning increments are much smaller than the mode spacing of these multimode cavities. The nearest mode to the lasing mode that can be identified in a subthreshold spectrum is more than 25 nm away.³ We have confirmed that these devices in Fig. 2 are lasing in the mode with a calculated cold-cavity quality factor (Q) of around 10^4 . This calculated Q value is nearly unchanged over an even larger range of PC lattice constants than is considered here. The quality factors and resonance frequencies of the microcavities were calculated by a combination of three-dimensional finite-difference time-domain method and Pade's interpola-

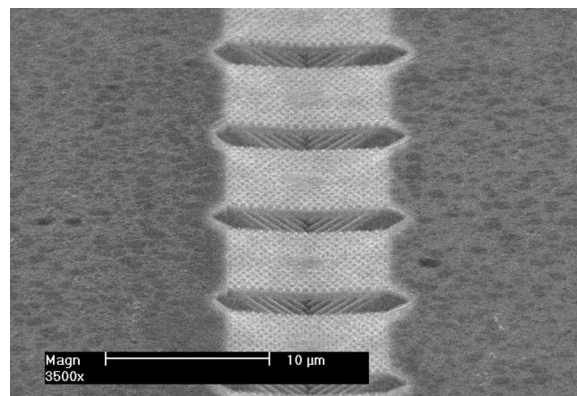


FIG. 1. An oblique view scanning electron microscopy image of a subset of the laser cavities in the array.

^{a)}Electronic mail: caoj@usc.edu

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 01 JUN 2005		2. REPORT TYPE N/A		3. DATES COVERED -	
4. TITLE AND SUBTITLE Threshold dependence on the spectral alignment between the quantum-well gain peak and the cavity resonance in InGaAsP photonic crystal lasers				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Department of Electrical Engineering and Electrophysics, University of Southern California, 3737 Watt Way, PHE 424, Los Angeles, California 90089				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited					
13. SUPPLEMENTARY NOTES See also ADM001923.					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 3	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

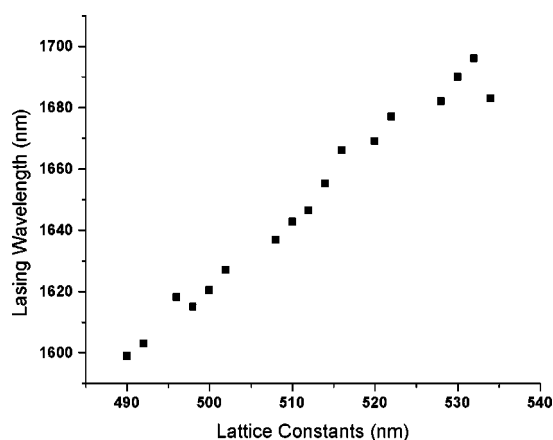


FIG. 2. The lasing wavelengths as a function of lattice constant for the 17 PC membrane lasers.

tion technique,⁴ in which the time domain responses of the field components are fast Fourier transformed and Pade interpolated thereafter to improve the accuracy of the frequency response.

It is important to note that the Q factor of the mode, which is lasing in the array, does not change appreciably over a wide range of lattice parameters. This claim is based on our numerical simulation results. To demonstrate the accuracy of the numerical simulation results used in this analysis, Fig. 3 shows the calculated resonant frequencies and their Q values for a cavity with lattice constant of 550 nm, which is outside the tuning range considered here. Also included in Fig. 3 is a lasing spectrum from a cavity with a lattice constant of 550 nm. For this cavity, the highest Q mode is no longer aligned with the gain peak, so that lasing occurs in shorter wavelength modes at higher threshold pump powers. This higher threshold pump power allows greater spontaneous emission intensity into the nonlasing modes, and therefore allows a better comparison between the calculated resonance frequencies and the observed spectra. To better illustrate the agreement between the observed frequencies and the calculated frequencies, we have shifted the calculated resonant frequencies in Fig. 3 by -0.0027 in normalized frequency, corresponding to about 12 nm in wavelength. This 12-nm shift corresponds to an error of less than

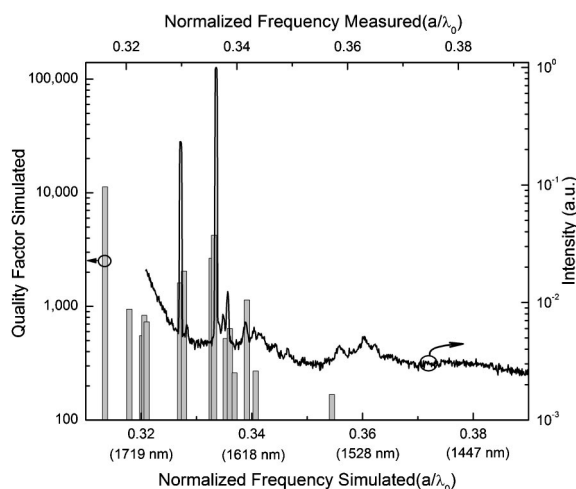


FIG. 3. Lasing spectrum from a cavity with lattice constant of 550 nm (dark line), and calculated resonant frequencies with Q factors for such a cavity.

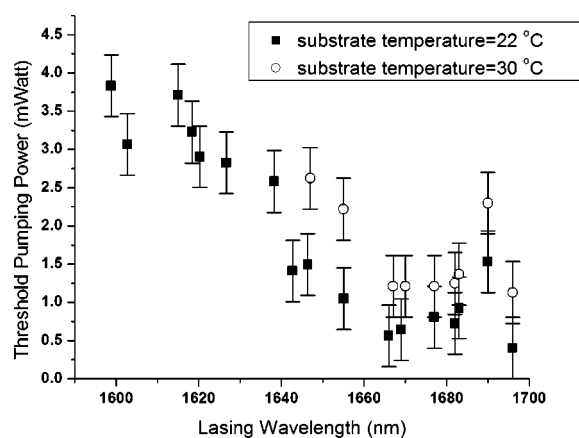


FIG. 4. Threshold pumping power vs lasing wavelength for the 17 PC lasers at two substrate temperatures.

1%, which is well within the error range of the dimensions of a real, fabricated device compared with numerical modeled dimensions.

Figure 4 shows the threshold pumping powers and lasing wavelengths of each laser in the array at a substrate temperature of 22 °C (square symbols). Since we believe the Q of this mode is not changed over this range of lattice constants, we attribute the approximately parabolic profile to the changing spectral alignment between the gain peak of the quantum well and the high- Q mode of each cavity. This trend is evident in the data, even though there are likely to be variations from one element of the array to the next due to fabrication imperfections. Similar behavior of the threshold condition has been observed in vertical cavity surface emitting lasers.^{5,6} The minimum threshold pumping power in Fig. 4 occurs near 1670 nm and corresponds to the point at which optical gain peak is aligned with the lasing mode. The threshold pumping power changes by more than a factor of 7 across the tuning range of the array. We have also measured the threshold pump powers of the lasers in this array at a slightly elevated substrate temperature of 30 °C. The result is represented by the circles in Fig. 4.

According to our previous results,⁷ a substrate temperature increase of a few degrees will cause only a several Angstrom shift in lasing wavelength. According to the data at 22 °C, a lasing wavelength shift of several Angstroms should cause only a slight change in the threshold pump power. However, the threshold pumping powers of the devices near 1670 nm increase by almost a factor of 2 with the 8 °C temperature increase, as shown in Fig. 4. This result we associate with a T_0 of the InGaAsP suspended membrane PC cavity if we represent the temperature dependence of threshold as $P_{th} \sim \exp(T/T_0)$. We note that even though there is a strong threshold dependence on the spectral alignment between the gain peak and cavity resonance, this effect does not dominate the temperature dependence of the lasers, owing to the small value of T_0 . The T_0 value extracted from this threshold data varies across the array from just under 10 to 21 K. These values are smaller than those in our previous report,⁷ but we note that the optical pump spot size and the pulse conditions used in this work differ from the previous work.

In conclusion, we have investigated the effects on the threshold pumping powers of membrane photonic crystal mi-

croavity lasers, which originate from the spectral alignment between quantum-well optical gain and cavity resonance.

This study is based on research supported in part by the U.S. Army Research Laboratory and the Army Research Office under contract no. DAAD19-99-1-0121, the Defense Advanced Research Projects Agency under contract no. N66001-00-C-8079, and the U.S. Air Force under contract no. F49620-02-1-0403. Computation for the work described in this letter was supported, in part, by the University of Southern California Center for High Performance Computing and Communications.

- ¹O. Painter, A. Husain, A. Scherer, P. T. Lee, I. Kim, J. D. O'Brien, and P. D. Dapkus, *IEEE Photonics Technol. Lett.* **12**, 1126 (2000).
- ²J. R. Cao, P. T. Lee, S. J. Choi, R. Shafiiha, S. J. Choi, J. D. O'Brien, and P. D. Dapkus, *J. Vac. Sci. Technol. B* **20**, 618 (2002).
- ³J. R. Cao, P.-T. Lee, S.-J. Choi, J. D. O'Brien, and P. D. Dapkus, *J. Nanosci. Nanotech.* **2**, 313 (2002).
- ⁴S. Dey and R. Mittra, *IEEE Microw. Guid. Wave Lett.* **8**, 415 (1998).
- ⁵B. Tell, K. F. Brown-Goebeler, R. E. Leibenguth, F. M. Baez, and Y. H. Lee, *Appl. Phys. Lett.* **60**, 683 (1992).
- ⁶K. D. Choquette, R. P. Schneider, Jr., and J. A. Lott, *Opt. Lett.* **19**, 969 (1994).
- ⁷P. T. Lee, J. R. Cao, S. J. Choi, Z. J. Wei, J. D. O'Brien, and P. D. Dapkus, *Appl. Phys. Lett.* **81**, 3311 (2002).